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Projected changes to extreme ice loads for overhead transmission lines across Canada

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ABSTRACT

Ice accretion on transmission lines can lead to serious damages from line breakage and flashover. This study investigates projected changes to design ice loads for overhead transmission lines for the 2041–2070 and 2071–2100 periods with respect to the 1976–2005 period over Canada, using transient climate change simulations of the fifth generation Canadian Regional Climate Model, for two driving Global Climate Models and two Representative Concentration Pathways. Projected changes to freezing rain characteristics are first evaluated and results suggest decreases in 50-year return levels of annual maximum daily freezing rain for the south-eastern inland and coastal regions and south-western and north-eastern coastal regions of North America, but increases for other regions. Consequently, the simulations suggest statistically significant increases in 50-year return levels of annual maximum ice thickness, particularly for regions of Quebec and west of the Hudson Bay (larger than 10 mm) and some scattered increases for south- central and western Canada (mostly smaller than 3 mm). This study also helped identify regions where both wind and ice loads will increase in future climate, which can be detrimental to the electric infrastructure. Results suggest that compound event assessments would be valuable, taking into consideration larger set of simulations, to obtain more robust projections.

1. Introduction

Ice storms and related ice accretion can result in severe disruptions to wind energy generation (Yang, Yu, Choisnard, Forcione, & Antic, 2015), urban functioning (Armenakis & Nirupama, 2014), forestry sector (Proulx & Greene, 2001), and electrical infrastructure including transmission and distribution structures and lines (Armenakis & Nirupama, 2014; Makkonen, Lehtonen, & Hirviniemi, 2014; Rezaei, Chouinard, Langlois, & Légeron, 2016). Ice accretion on overhead transmission lines, in particular, can result in serious damages due to line breakage, tower failure and flashover. Therefore, ice thickness and wind pressure are key environmental loads considered individually in the design of overhead transmission lines to ensure that the lines have both sufficient mechanical strength and reliability (Canadian Standards Association, 2010; Rezaei et al., 2016). According to the fifth assessment report of the Intergovernmental Panel on Climate Change (IPCC), the global mean temperature will increase by 4.8 °C by the end of the 21st century, compared to the pre-industrial climate, if greenhouse gas emissions continue unabated (IPCC, 2013). The warmer temperatures can impact the frequency and intensity of ice storms, which are frequently associated with surface air temperatures between −10 °C to 0 °C (Cortinas, Bernstein, Robbins, & Walter Strapp, 2004), and therefore it is important to evaluate how ice loads might change in the future due to this anticipated warming or climate change. The design ice load is based on selected return levels obtained from annual maximum ice thickness time series. Projected changes to these return levels in a future warmer climate can have significant implications for existing transmission lines, which were designed based on the ice loads estimated from historical observations of freezing rain and wind speed (Panteli & Mancarella, 2015).

A number of models have been proposed to estimate ice accretion on overhead lines exposed to ice storms from meteorological data such as the amount and duration of freezing rain, wind speed and direction, and air temperature (Chainé & Castonguay, 1974; Jones, 1998; Makkonen, 1998; Yip, 1995). Using these approaches, several studies have proposed/published extreme ice accretion maps for the design of overhead transmission lines as well as ice accretion risk assessments (Canadian Standards Association, 2010; Lamraoui, Fortin, Benoit, Perron, & Masson, 2013; Nygaard, Seierstad, & Veal, 2014; Zhu, Liu, Yang, & Li, 2014). Very few studies have focused on the future changes

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to ice thickness/loads and associated impacts on overhead transmission lines. Rezaei et al. (2016) evaluated changes in the reliability of overhead transmission lines to changes in ice loads, based on a range of assumed changes in the mean and standard deviation of future ice thickness. They highlighted the need for local and regional scale climate change scenarios to complete a comprehensive risk analysis and a quantitative assessment of climate change impacts on transmission lines. However, regional-scale projections of ice thickness characteristics based on downscaled scenarios from global climate models (GCMs) are not yet widely available for Canada.

Regional climate models (RCMs) have been employed in many regional-scale studies to dynamically downscale GCM climate projections to analyze climate change impacts on different extreme events. The fifth-generation Canadian Regional Climate Model (CRCM5), which is based on the numerical weather prediction model of Environment and Climate Change Canada (ECCC), has been successfully applied to evaluate projected changes to different extreme events and environmental loads such as temperature extremes (Diro et al., 2014; Diro & Sushama, 2017; Jeong, Sushama, Diro, & Khaliq, 2016; Jeong, Sushama, Diro, Khaliq, Beltrami et al., 2016), precipitation extremes (Mladjic et al., 2011), floods (Clavet-Gaumont, Sushama, Khaliq, Huziy, & Roy, 2012; Huziy et al., 2012; Jeong, Sushama, Khaliq, & Roy, 2014; Poitras, Sushama, Seglenieks, Khaliq, & Soulis, 2011; Sushama, Laprise, Caya, Frigon, & Slivitzky, 2006), droughts (Jeong, Sushama, & Khaliq, 2014; Poitras et al., 2011; PaiMazumder, Sushama, Laprise, Khaliq, & Sauchyn, 2012; Sushama, Khaliq, & Laprise, 2010), rain-on-snow events (Jeong & Sushama, 2018a), and wind and snow loads (Jeong & Sushama, 2018b). Jeong and Sushama (2018b) showed some increases in design wind pressure for central and eastern Canada, due to changes in inter-annual variability of annual maximum wind speed and general decreases (increases) in design snow load for southern (northern) Canada, for the future 2071–2100 period with respect to the 1981–2010 period.

The main purpose of this study is to evaluate projected changes to ice accretion/loads (i.e., 50-year return level of radial ice thickness) used in the design of overhead transmission lines for two future periods (2041–2070 and 2071–2100), with respect to the current 1976–2005 period, across Canada, using CRCM5 simulations, driven by two GCMs (i.e., the Canadian Earth System Model 2 (CanESM2) and the Max-Planck-Institut Earth System Model (MPI-ESM)) for Representative Concentration Pathways (RCP) 4.5 and 8.5 scenarios. The RCPs are a set of greenhouse gas concentration trajectories designed to support research on the impacts of climate change, and the 4.5 and 8.5 scenarios correspond to radiative forcings of 4.5 and 8.5 W/m^2 by the end of the 21st century compared to pre-industrial values (IPCC, 2013). The 50-year return levels are considered as the National Building Code of Canada generally provides these for various regions of Canada. The extreme value assessment conducted in this study uses 3-h radial ice thickness, which is derived from freezing rain, wind speed, and air temperature. As freezing precipitation is the main climate variable determining the radial ice thickness, projected changes to freezing rain characteristics (i.e., frequency, amount, and 50-year return levels of daily freezing rain) are also assessed in this study. Finally, summary maps showing regions where both ice and wind loads are projected to increase in future climate for the scenarios considered in this study are presented.

2. Model and datasets

The CRCM5 is based on the Global Environmental Multiscale (GEM) model used for numerical weather prediction at Environment and Climate Change Canada (Côté et al., 1998). Therefore, the physical parameterizations in CRCM5 are similar to those in GEM, except for the land surface scheme. Particularly, CRCM5 uses the Kain and Fritsch (1992) deep-convection scheme and the Bélair, Mailhot, Girard, and Vaillancourt (2005) shallow-convection scheme. The resolvable large-scale precipitation is modeled by employing Sundqvist, Berge, and Kristjánsson (1989), while radiation is parameterized by Correlated K solar and terrestrial radiation of Li and Barker (2005). This model employs the interactive Flake lake model (Mironov et al., 2010) and Canadian Land Surface Scheme (CLASS) 3.5 (Verseghy, 2012), for the land part. This version of CLASS includes prognostic equations for energy and water conservation for a user-defined number of soil layers and thermally and hydrologically distinct snowpack where applicable (treated as an additional variable-depth soil layer). The thermal budget is performed over all soil layers but the hydrological budget calculations are performed only for layers above bedrock. An explicit vegetation canopy has its own energy and water balance with prognostic variables for canopy temperature and water storage. CRCM5 employs one-way nesting downscaling procedure. It interpolates lateral boundary variables (i.e., wind, air temperature, humidity and pressure) obtained from reanalysis and GCM simulations to its grid points progressively. The other climate variables such as precipitation are calculated based on the interpolated progressive variables and relevant parameterization schemes. Four precipitation types (i.e., snow, ice pellets, freezing rain, and rain) or mixtures of these types are diagnosed following Bourgouin (2000). When precipitation occurs, the vertical temperature profile is the main determinant of the precipitation type. Detailed procedure can be found in Bourgouin (2000).

The CRCM5 simulations used in this study are the same as those used in Jeong and Sushama (2018a,b). The CRCM5 experimental domain covers whole of North America and neighbouring oceans at 0.44° horizontal resolution. The three simulations considered in this study for the current 1976–2005 period are driven by ECMWF (European Centre for Medium-Range Weather Forecasts) gridded ERA-Interim reanalysis dataset (Dee et al., 2011), CanESM2 (Arora et al., 2011), and MPI-ESM (Giorgetta et al., 2013) at the lateral boundaries. The simulation driven by the ERA-Interim reanalysis (CRCM5-ERA hereafter) for the 1976–2005 period is used for the evaluation of the RCM skill. The CRCM5 simulations driven by CanESM2 and MPI-ESM for the 1976–2005 period used in this study will be referred to as CRCM5-CanHist and CRCM5-MPIHist hereafter, which are used as references of current climate as well as to evaluate boundary forcing errors, when compared to the CRCM5-ERA. Two CRCM5 simulations driven by CanESM2 for the RCP4.5 and RCP8.5 pathways and one simulation driven by MPI-ESM for the RCP4.5 pathway, for the 2041–2071 and 2071–2100 periods are also considered for assessing projected changes; these will be referred to as CRCM5-CanRCP4.5, CRCM5-CanRCP8.5, and CRCM5-MPIRCP4.5 to reflect both the boundary forcing dataset and emission pathways considered.

For validating simulated freezing rain characteristics, National Centers for Environmental Prediction (NCEP) North American Regional Reanalysis (NARR) dataset is used. NARR reanalysis is a long-term, consistent, high-resolution reanalysis dataset for the North American domain (Mesinger et al., 2006) and provides the same precipitation types as in CRCM5. Furthermore, NARR is known to provide an improved reanalysis of overall atmospheric circulation throughout the troposphere compared to previous global reanalysis (Mesinger et al., 2006). Table 1 provides a summary of all reanalysis, GCM, and CRCM5 simulations considered in this study.

3. Methodology

Prior to the investigation of future projections to the design ice load, the ability of the CRCM5 in simulating freezing rain is studied. CRCM5-ERA, -CanHist, and -MPIHist simulated freezing rain is evaluated by comparing the frequency and magnitude as well as their spatial patterns with those from NARR reanalysis over North America for the 1979–2005 period.

Eq. (1), suggested by Jones (1998), is used to calculate the amount of ice accumulation from the 3-h freezing rain, 10-m wind speed, and 2-m air temperature of CRCM5 simulations over Canada.

Table 1
Summary of the reanalysis, GCM, and CRCM5 simulations considered in the study.

Name	Explanation
ERA	Girdded ERA-Interim reanalysis dataset (Dee et al., 2011)
NARR	North American Regional Reanalysis dataset (Mesinger et al., 2006)
CanESM2	Canadian Earth System Model version 2 (Arora et al., 2011)
MPI-ESM	Max-Planck-Institut Earth System Model (Giorgetta et al., 2013)
CRCM5	Fifth-generation Canadian Regional Climate Model
CRCM5-ERA	CRCM5 simulation driven by ERA-Interim reanalysis dataset for the 1976–2005 period
CRCM5-CanHist	CRCM5 simulation driven by CanESM2 dataset for the current (1976–2005) period
CRCM5-MIPHist	CRCM5 simulation driven by MPI-ESM dataset for the current period
CRCM5-CanRCP4.5	CRCM5 simulation driven by CanESM2 dataset for RCP4.5 scenario for the future (2041–2070 & 2071–2100) periods
CRCM5-CanRCP8.5	CRCM5 simulation driven by CanESM2 dataset for RCP8.5 scenario for the future periods
CRCM5-MPIRCP4.5	CRCM5 simulation driven by MPI-ESM dataset for RCP4.5 scenario for the future periods

$$R = \frac{1}{\rho_i \pi} \sum_{j=1}^{N} [(P_j\rho_0)^2 + (3.6V_jW_j)^2]^{1/2} \tag{1}$$

where N is the number of hours of freezing precipitation, P_j and V_j are the precipitation rate (mm/h) and wind velocity (m/s), and $W_j = 0.067P_j^{0.846}$ is the liquid water content (g/m^3) of the rain-filled air in the jth hour. ρi and ρ0 are the density of glaze ice (0.9 g/cm^3) and water (1 g/cm^3). This method is selected as it is easy to use and shows similar results to the other methods such as MRI (MRI, 1997), Makkonen (Makkonen, 1998), and CRREL (Jones, 1996) methods. This method has also been applied in many studies (e.g., Rezaei et al., 2016; Zhu et al., 2014). The wind direction is assumed to be perpendicular to the cable axis and ice accretion continues until either the air temperature increases to above 1 °C or 7 days have passed without freezing precipitation (Canadian Standards Association, 2010). In reality, electrical utilities may deploy ice monitoring and removal programs to mitigate the effects of ice accumulation on electrical infrastructure.

For all CRCM5 simulations, annual maximum time series of 3-h ice thickness are prepared for all grid points located over Canada for the current (1976–2005) and future (2041–2070 and 2071–2100) periods. Estimation of the 50-year return level of radial ice thickness on overhead transmission lines is carried out based on the Gumbel distribution, which is the same distribution considered for extreme ice thickness analysis on overhead transmission lines in the Canadian Standards Association (2010). Projected changes to the design ice thickness are then estimated for the 2041–2070 and 2071–2100 periods with respect to the 1976–2005 period over Canada. Statistical significance is tested for the null hypothesis that the difference of the 50-year return levels between the current and future periods is different from zero at the 10% two-sided significance level using the bootstrap approach with 200 resamples. Although Jeong and Sushama (2018b) already reported the projected changes to design wind pressure, this study presents summary maps that display the regions where both future design ice thickness and wind pressure are projected to increase over Canada.

4. Results

Fig. 1 shows the spatial distribution of monthly means of NARR and modeled (CRCM5-ERA, -CanHist, and -MPIHist) freezing rain days and associated rainfall amount for the 1979–2005 common period between NARR and CRCM5 simulations. The spatial patterns of both NARR and CRCM5 simulated freezing rain days vary from month to month. Freezing rain frequency of the NARR and CRCM5 simulations are higher for the middle-eastern coastal regions of North America in November. The regions of high frequency migrate further south in January and then move back north in March and May, following the freezing line. CRCM5 simulations show good spatial agreement with NARR for the freezing rain frequency, though they show lower frequency for November, January, and March but higher frequency for May compared to NARR. The CRCM5 simulations exhibit very similar spatial patterns with one another, indicating that the boundary forcing errors, i.e. the errors stemming from the errors in the driving data, which are reflected in the differences between RCM simulations driven by GCMs and ERA-Interim reanalysis, are generally modest. These spatial distributions of freezing rain days are generally consistent with those in Cortinas et al. (2004). Cortinas et al. (2004) developed the spatial distribution maps of freezing rain days based on hourly wind speed dataset observed at 609 meteorological stations for the United States and Canada obtained from the National Climate Data Center (NCDC) for the 1976–1990 period. It is notable that the spatial distribution of freezing rain days of CRCM5 simulations yield better agreement with Cortinas et al. (2004) than NARR. Overall spatial patterns of both NARR and CRCM5 simulations for freezing rain amount are similar to those of freezing rain days.

Fig. 2 shows projected changes to monthly freezing rain days and amount for CRCM5-CanRCP4.5, -CanRCP8.5, -MPIRCP4.5. The simulations suggest increases in the future freezing rain days to the north of the future freezing line, particularly from November to March. The CRCM5 simulations, however, show general decreases in the freezing rain days to the south of the future freezing line. The magnitude and areal extent of decreases for each simulation will depend among other factors on the projected increases in surface temperature, which is reflected in the differences between current and future freezing lines. These results are in a good agreement with the findings of Cheng, Li, and Auld (2011) for eastern Canada. Based on statistically downscaled outputs from eight GCMs, they reported increases/decreases in freezing rain days in the cold (December–February)/warm (November and April) months for the future 2081–2100 period compared to the historical 1958–2007 period. They also reported overall increases in freezing rain days over eastern Canada for late this century as the decreases in future freezing rain days in the warm months were projected to be much less compared to the increases in the cold months. The projected changes to the freezing rain days show different spatial distributions depending on the driving GCM and emission scenario. CRCM5-MPIRCP4.5 suggests the smallest changes while CRCM5-CanRCP8.5 yields the largest changes for the freezing rain days. It must be noted that CanESM2 generally suggests larger changes in temperature compared to MPI-ESM (Šeparović et al., 2013), which is also reflected in the CRCM5 simulations (see the current and future freezing lines). Consequently, the CRCM5 simulations driven by CanESM2 suggested larger changes in rain-on-snow frequency compared to those driven by MPI-ESM (Jeong & Sushama, 2018a). Projected changes for the CRCM5-CanRCP4.5 suggest smaller changes in the freezing rain frequency compared to those for the CRCM5-CanRCP8.5, associated with smaller increases in future mean surface temperature and precipitation frequency. Again, overall spatial patterns of the three CRCM5 simulations for projected changes to freezing rain amount are similar to those of freezing rain days.

Fig. 3 displays spatial distributions of 50-year return levels of annual maximum daily freezing rain for NARR and CRCM5 current simulations and projected changes to the 50-year return levels for the three CRCM5 future simulations. The 50-year return levels of annual maximum daily freezing rain are estimated using the Gumbel

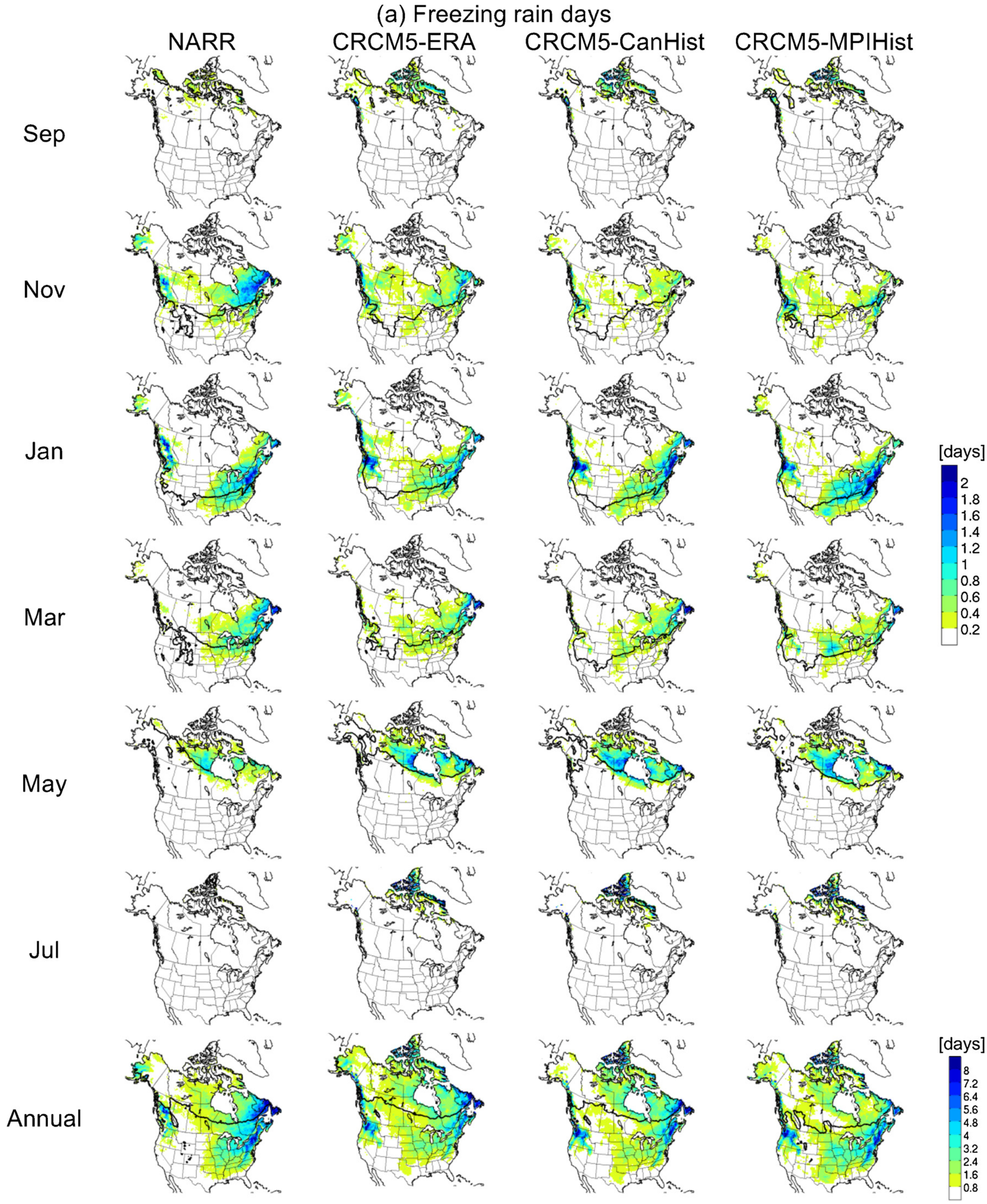

Fig. 1. Monthly and annual means of freezing rain (a) days and (b) amount for the 1979–2005 period from NARR, CRCM5-ERA, CRCM5-CanHist, and CRCM5-MPIHist. The black contour represents the mean freezing line.

distribution in the same way as in the case of ice thickness. Again, the spatial distribution of the 50-year return level for the CRCM5-ERA is generally consistent with the contour map of median annual freezing rain days given in Cortinas et al. (2004) over North America and also that of total freezing rain hours given in Cheng et al. (2011) over eastern Canada. The three future simulations broadly suggest similar spatial patterns to the projected changes to the 50-year return levels, as they yield decreases for the south-eastern inland and coastal regions and south-western and north-eastern coastal regions of North America, but significant increases for eastern Canada in the two CanESM2 driven simulations and scattered increases for western parts of North America in all three simulations. Increases larger than 10 mm are projected for some grids located in the eastern parts of NA based on the CanESM2 driven simulations, but increases smaller than 5 mm are noted for the western and central parts of NA. The projected changes for the three simulations, however, exhibit quite different patterns on a regional scale by reflecting the influence of the driving GCM and emission scenario. Again, CRCM5-CanRCP8.5 suggests the largest changes and yields statistically significant increase for the western parts of Canada while CRCM5-MPIRCP4.5 shows the smallest changes for the 50-year return levels. The projected changes for the 2071–2100 period yield larger decreases for the south-eastern parts and north eastern coastal regions of NA, compared to those for the 2041–2070 period, due to larger increases in surface air temperature.

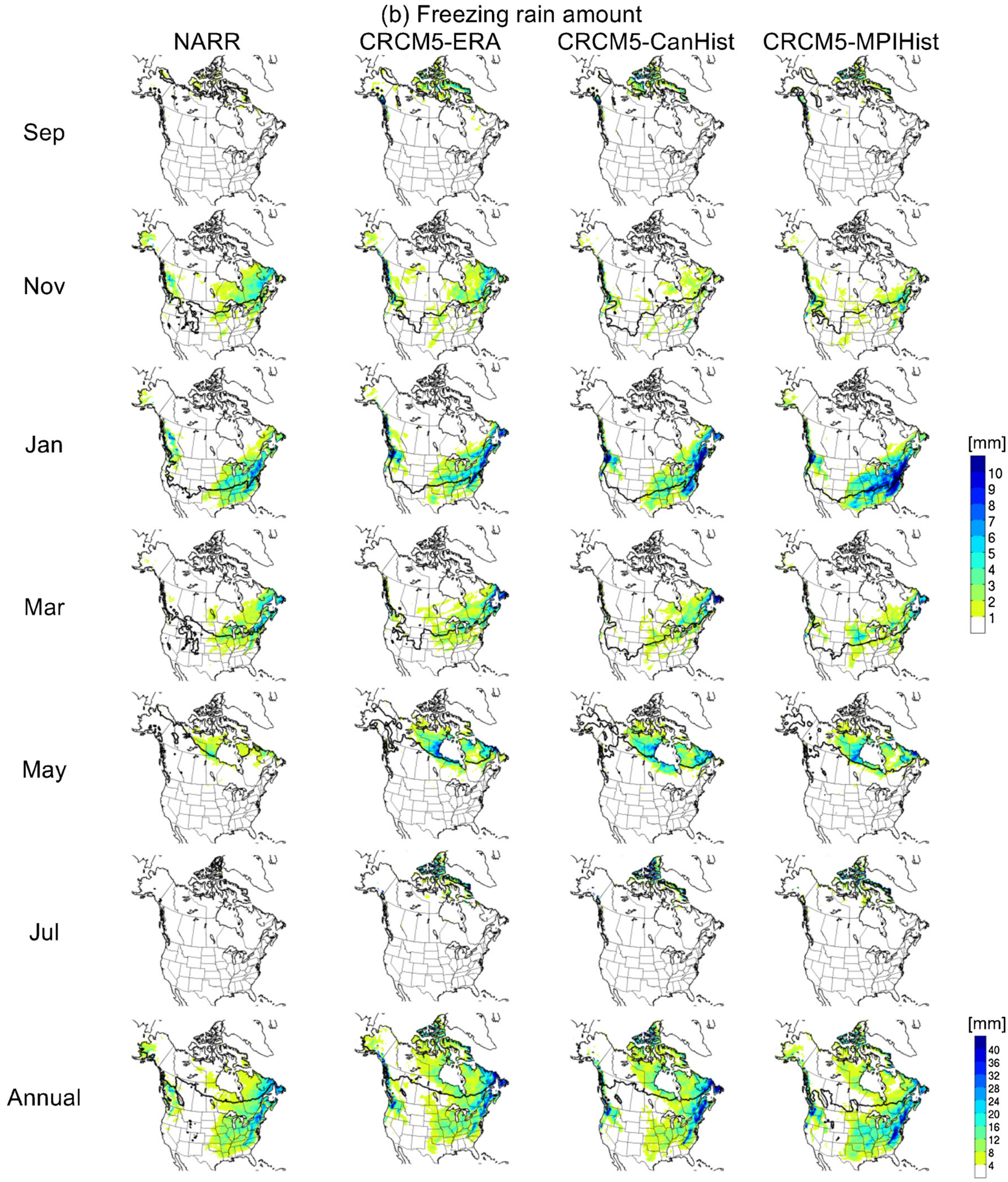

Fig. 1. (*continued*)

Spatial distributions of 50-year return levels of annual maximum 3-h radial ice thickness for NARR and CRCM5 current simulations over Canada are presented in Fig. 4a. Canadian Standards Association (2010) presents 50-year return levels of annual maximum hourly radial ice thickness in its Fig. CA.10 for eastern Canada and Fig. CA.11 for western Canada. These were developed based on ice accretion values from a conceptual model applied to about 200 meteorological stations for the period 1953–2006. Aside these CSA maps, so far, no other comparable research is available. The spatial distributions of the 50-year return levels for CRCM5 are in good agreement with the Canadian Standards Association (2010) contour maps. Regionally, the 50-year return levels show larger values for the Atlantic and Hudson Bay coastal regions as well as northern Quebec, but smaller values for the western and central parts of Canada, which are well reproduced by the three CRCM5 simulations. NARR shows quite different spatial patterns from the CRCM5 simulations. It yields smaller values for the Hudson Bay coastal regions and northern Quebec but larger values for south-western Canada, compared to CRCM5 simulations as well as the contour maps presented in Canadian Standards Association (2010). These differences are also noted in the 50-year return levels of annual maximum daily freezing rain (Fig. 3a).

Projected changes to the mean, coefficient of variation (CV) and 50-year return levels of annual maximum 3-h radial ice thickness for the three future simulations are presented in Fig. 4b. The simulations suggest statistically significant increases in the 50-year return levels, particularly for regions of Quebec and west of the Hudson Bay (larger than 10 mm in some cases), based on increases in mean and/or inter-annual variability (i.e., CV) of annual maximum 3-h ice thickness. Some scattered increases are also seen for the south-central and western parts (mostly smaller than 3 mm). Larger future inter-annual variability of

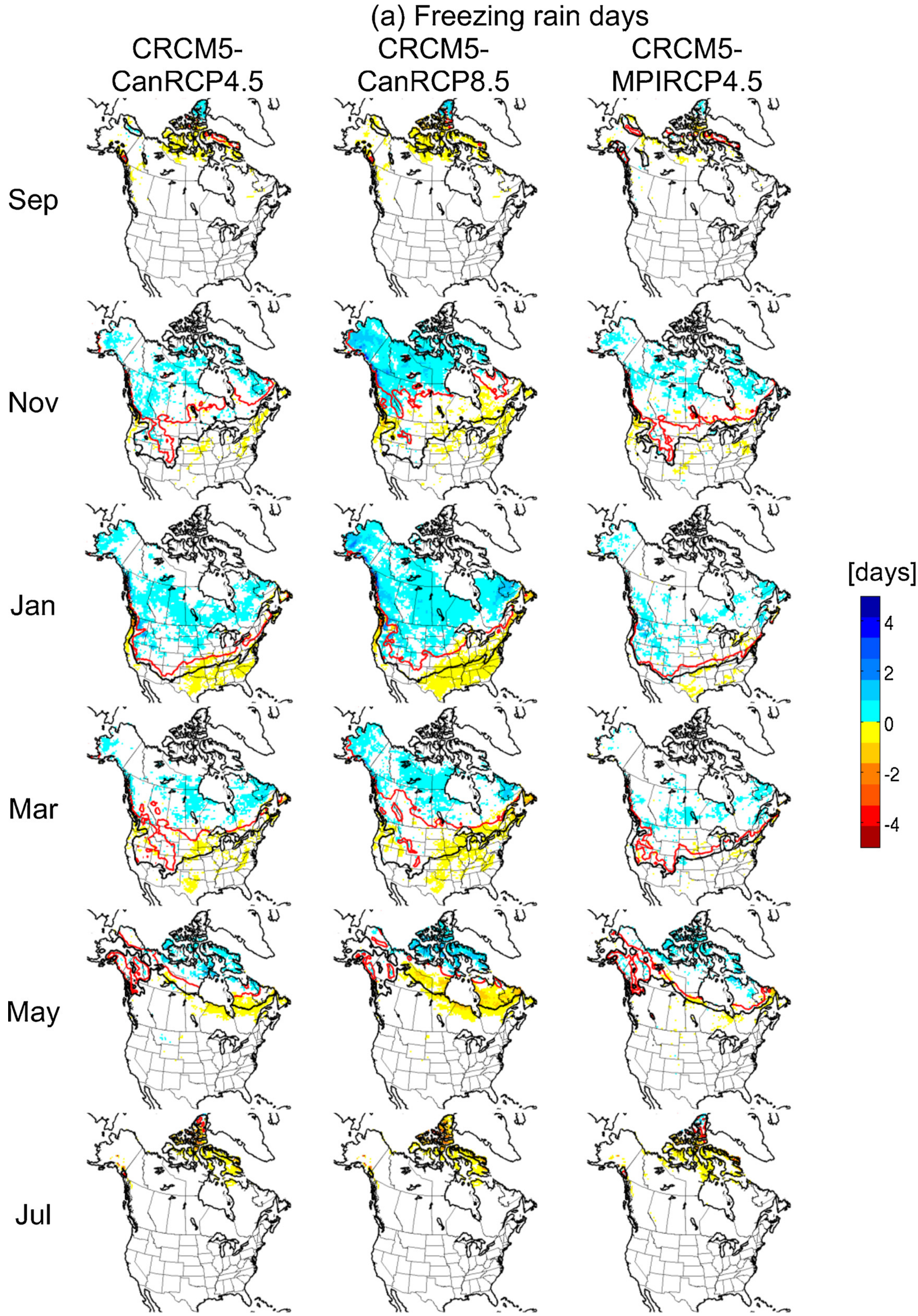

Fig. 2. Projected changes to (a) the number of freezing rain days and (b) amount for the three CRCM5 simulations (i.e., CRCM5-CanRCP4.5, CanRCP8.5, and CRCM5-MPIRCP4.5) for the 2071–2100 period with respect to the 1976–2005 period. The black and red contours represent the mean freezing line in current and future climates. Projected changes are shown when they are statistically significant with the two-sample *t*-test at the 10% significance level.

the ice thickness leads to statistically significant increases in the 50-year return level for many grid points located in western and central Canada. Spatial distributions of the three simulations for the projected changes to the 50-year return level of the ice thickness display a good agreement with those of the freezing rain, suggesting the changes in extreme freezing rain is the main attributable component to the changes in

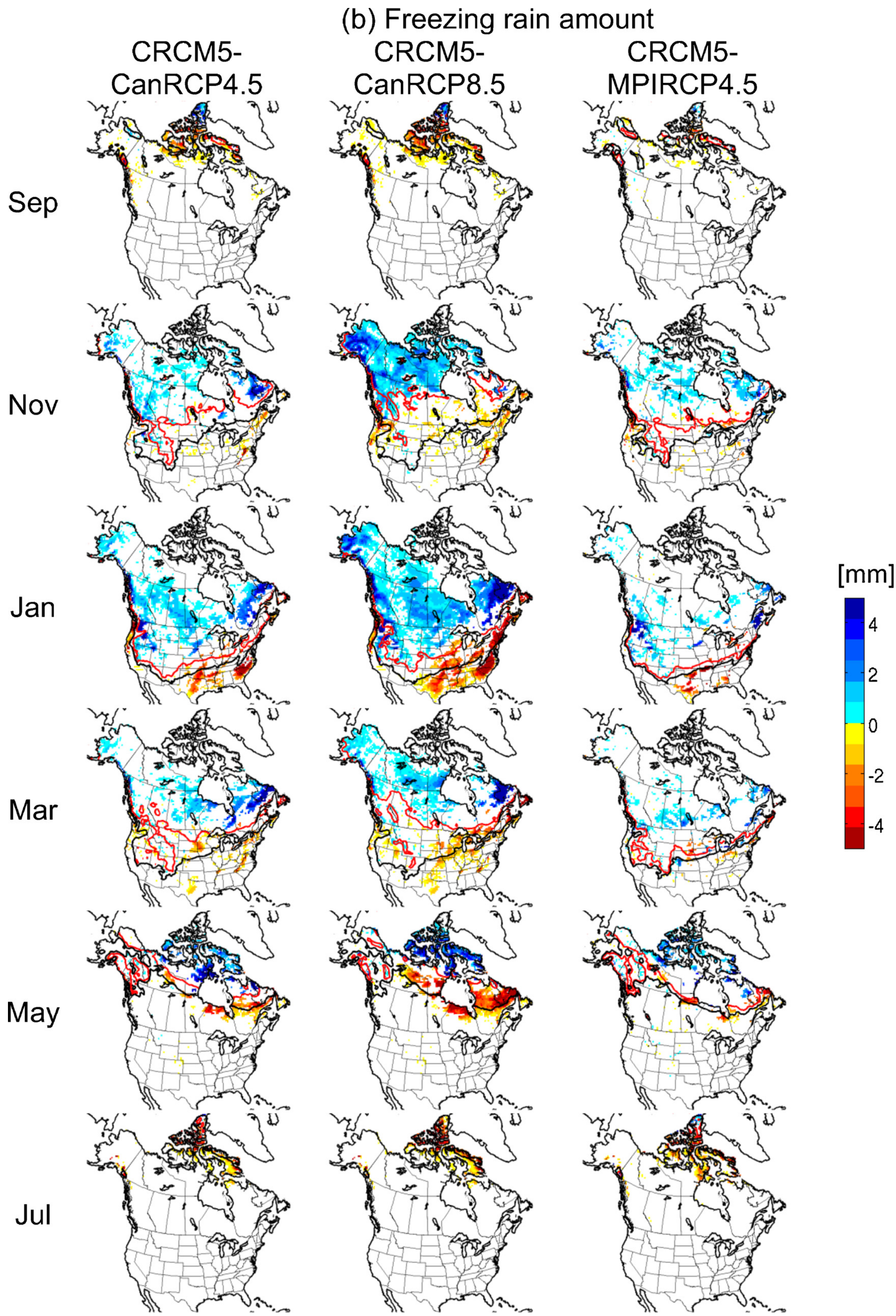

Fig. 2. (*continued*)

future extreme ice thickness. It is notable that CRCM5-CanRCP8.5 suggests larger decreases or smaller increases in the design ice thickness for the eastern coastal and Great Lakes regions compared to CRCM5-CanRCP4.5 for the 2071–2100 period, due to larger increases in surface air temperatures and associated larger decreases in freezing rain in CRCM5-CanRCP8.5. These patterns are also visible in CRCM5-CanRCP8.5 for the 2071–2100 period, compared to the 2041–2070 period. Again, CRCM5-MPIRCP4.5 suggests the smallest changes for the

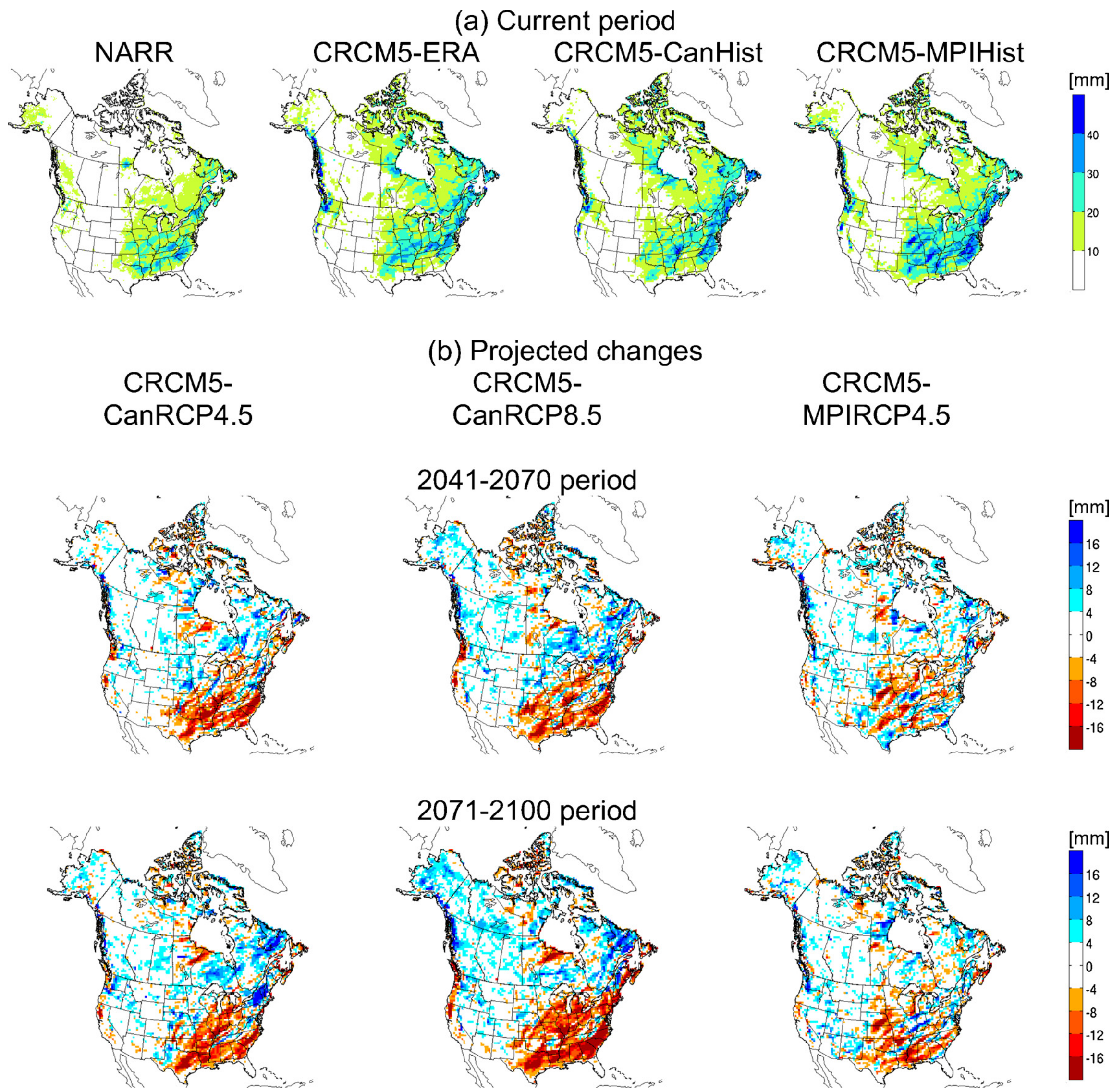

Fig. 3. 50-year return levels of annual maximum daily freezing rain for (a) NARR, CRCM5-ERA, CRCM5-CanHist, and CRCM5-MPIHist for the 1979–2005 period and (b) their projected changes for CRCM5-CanRCP4.5, -CanRCP8.5 and -MPIRCP4.5 for the future 2041–2070 and 2071–2100 periods with respect to the current 1976–2005 period.

return levels.

Jeong and Sushama (2018b) reported projected changes to the 50-year return levels of annual maximum 3-h wind pressure, which is directly proportional to the square of the wind speed, for the three simulations for the 2071–2100 period. As their current period starts 5 years later than this study, the projected changes are modified based on the current period considered in this study (Fig. 5a). Although Fig. 5a is provided for a better understanding of Fig. 5b (discussed later), projected changes in terms of both amounts and spatial patterns are very similar to that of Jeong and Sushama (2018b), despite the differences in the current periods. It must be noted that the projected changes to the 50-year return level of the wind pressure show more spatial variability compared to those of the ice thickness, as extreme wind speed is basically affected by regional-scale air circulations associated with instantaneous surface temperature and air pressure gradients and many other similar effects. Moreover, projected changes to the 50-year return level of wind pressure are strongly influenced by the inter-annual variability in annual maximum wind speed rather than those in the mean values (Jeong & Sushama, 2018b).

Based on the projected changes to the design ice thickness (Fig. 4b) and wind pressure (Fig. 5a), maps, which display the regions where both environment loads are projected to increase, for the three future simulations are presented in Fig. 5b. In the figure, 4 categories are defined based on increases less than or greater than 13% for the two variables – the 13% threshold is chosen as it approximately corresponds to the difference between current 100 and 50 year return values for ice thickness and wind pressure (see Table CA.2 of Canadian Standards Association (2010)). The superposed maps suggest increases in both ice and wind loads for some regions, specifically for CRCM5-CanRCP4.5 over south-western and north-eastern parts, for CRCM5-MPIRCP4.5 over central and north-eastern parts, and for CRCM5-CanRCP8.5 over western and eastern near-coastal parts of Canada.

5. Summary and discussion

This study investigates projected changes to design radial ice thickness or ice loads for 10-m high overhead transmission lines for the future 2041–2070 and 2071–2100 periods with respect to the current 1976–2005 period over Canada, using CRCM5 simulations, for RCP 4.5 and 8.5 scenarios and two driving GCMs. Ice accretions are calculated based on freezing rain, wind speed, and air temperature. As surface air temperature and wind speed of CRCM5 have been presented in other

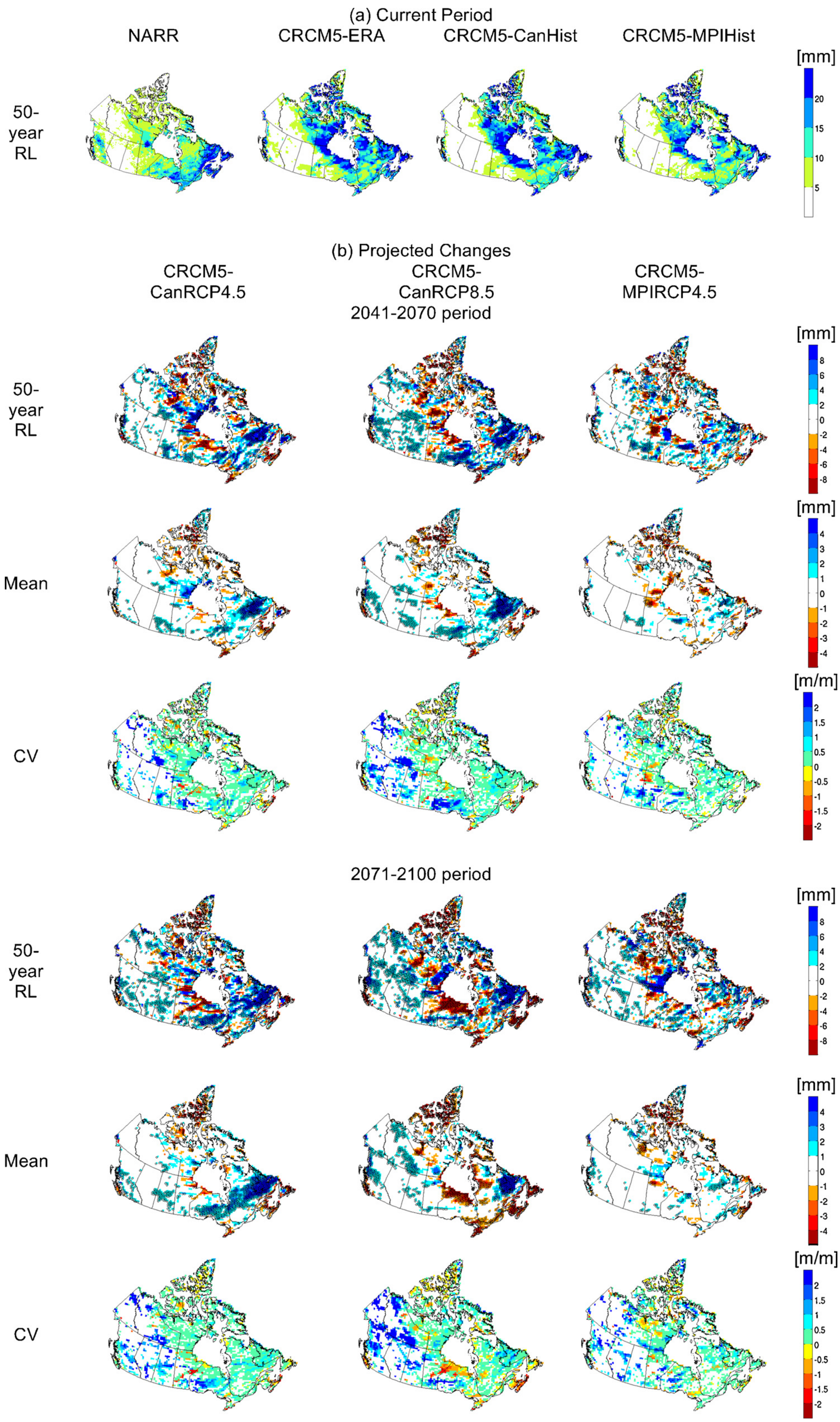

Fig. 4. 50-year return levels of annual maximum 3-h radial ice thickness for (a) NARR for the 1979–2005 period and CRCM5-ERA, -CanHist, and -MPIHist for the current 1976–2005 period and (b) their projected changes for CRCM5-CanRCP4.5, -CanRCP8.5, and -MPIRCP4.5 for the future 2041–2070 and 2071–2100 periods with respect to the current period. Projected changes to mean and coefficient of variation (CV) of the annual maximum ice thickness for the three simulations are also provided in (b). Projected changes are marked by open circles when they are statistically significant with two-sample *t*-test for mean and bootstrap approach for 50-year return level at the 10% significance level.

studies (i.e., Martynov et al., 2013; Jeong & Sushama, 2018b), current and future freezing rain characteristics (i.e., frequency, amount, and extreme values) as simulated by CRCM5 are presented in this study. Comparison of ERA-Interim driven CRCM5 (CRCM5-ERA) to NARR reanalysis and previous studies (i.e., Cortinas et al., 2004; Cheng et al., 2011) indicates that the RCM is able to reproduce observed spatial patterns of freezing rain. Consequently, design ice thickness obtained from CRCM5-ERA is in good agreement with the ice thickness contour maps of Canadian Standards Association (2010). Results suggest modest boundary forcing errors as the two GCM driven simulations (i.e., CRCM5-CanHist and -MPIHist) yield similar results to those of CRCM5-ERA for the freezing rain characteristics as well as annual maximum 3-h

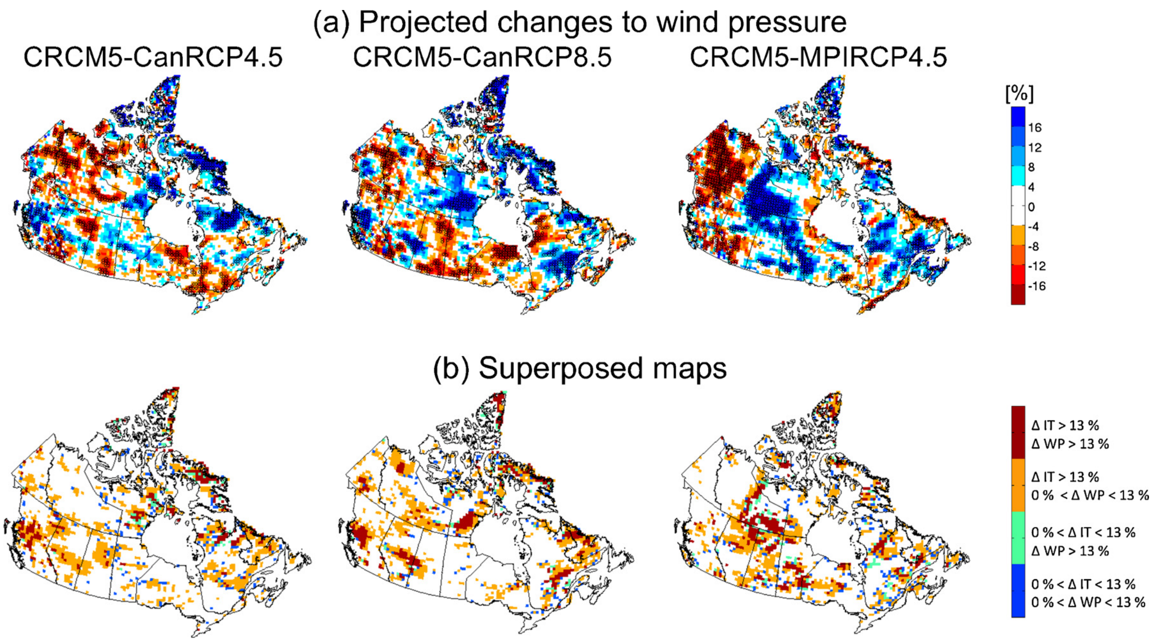

Fig. 5. (a) Projected changes to 50-year return level of annual maximum 3-h wind pressure for CRCM5-CanRCP4.5, -CanRCP4.5, and -MPIRCP4.5 for the future 2071–2100 period with respect to the current 1976–2005 period. Projected changes are marked by open circles when they are statistically significant with bootstrap approach at the 10% significance level. Superposed maps of the three future simulations are presented in (b) for displaying the regions where both 50-year return levels of ice thickness and wind pressure are projected to increase.

ice thickness.

The three future simulations suggest decreases in the 50-year return levels of the annual maximum daily freezing rain for south-eastern parts, significant increases for north-eastern parts, and scattered increases for western parts of the North American domain. However, the projected changes based on the CRCM5 simulations exhibit some differences at regional scale with driving GCMs and emission scenario. CRCM5-CanRCP8.5 suggests the largest changes, while CRCM5-MPIRCP4.5 shows the smallest changes to the return levels. The three future simulations also suggest statistically significant increases and decreases in 50-year return level of annual maximum 3-h radial ice thickness for many regions over Canada. These projections are in good agreement with those for the 50-year return level of annual maximum daily freezing rain, suggesting that freezing rain is the main attributable driver for the changes in future extreme ice thickness. The three simulations also show that larger future inter-annual variability of annual maximum ice thickness can lead to increases in extreme ice thickness in western and central Canada. The changes of extreme ice thickness are highly dependent on the changes of air temperature as CRCM5-CanRCP8.5 suggests larger decreases or smaller increases in the design ice thickness for the eastern coastal and Great Lakes regions compared to CRCM5-CanRCP4.5. As extreme wind pressure is also an important environment load, which should be considered along with ice loads in the design of overhead transmission lines, this study provides preliminary maps (Fig. 5b) that illustrate regions where both design loads are projected to increase in the future. According to the methodology adopted in the preparation of this map, the maximum wind and ice loads needn't occur at the same time for the identified regions, as the maximum loads were calculated independently. Combinations of ice thickness and wind speed that are not extremes per se could also lead to extreme/critical conditions for transmission lines. Therefore, joint occurrence assessments would be necessary to evaluate future reliability of overhead transmission lines. Such compound events will have different level of impacts depending on if they happen during the shoulder months with relatively lower energy demand or in the winter months with high demand.

The projected changes to extreme ice thickness derived in this study, based on the high-resolution CRCM5 simulations, can be useful to support development of climate-resilient design standards, codes and guides for overhead transmission lines. However, the extreme ice thickness for CRCM5 is derived from 3-h data. As Canadian Standards Association (2010) presents design ice thickness based on hourly observations, further investigation is required to verify CRCM5 performance as well as projected changes, when hourly simulation outputs will become available in the future. Furthermore, the CRCM5 with three different GCM projections suggest regionally different projections dependent on the driving GCM and emission scenario. Therefore, larger ensemble members including other RCMs and driving GCMs are required to properly evaluate uncertainties in the future projections and find robust climate change signals.

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